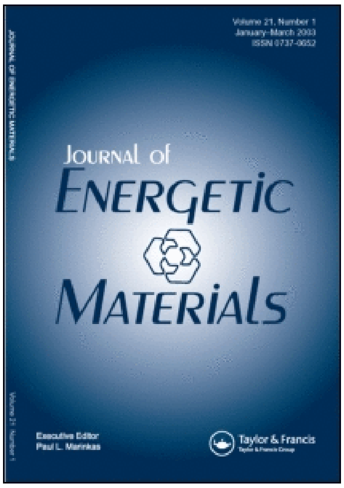

Journal of Energetic Materials
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713770432

# The behaviour of non-ideal explosives in the Ballistic Mortar

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**To cite this Article** Leiper, Graeme A.(1989) 'The behaviour of non-ideal explosives in the Ballistic Mortar', Journal of Energetic Materials, 7: 4, 381 — 404

**To link to this Article: DOI:** 10.1080/07370658908014905

**URL:** http://dx.doi.org/10.1080/07370658908014905

# THE BEHAVIOUR OF NON-IDEAL EXPLOSIVES IN THE BALLISTIC MORTAR

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An analysis has been developed for the Ballistic Mortar test based on classical mechanics and a two stage chemical reaction rate model. Non-ideal behaviour of the composition was modelled by partial energy release during the detonation phase and secondary exothermic processes during the expansion phase. Erosive grain burning and time delayed reactions were both considered. Gas loss from the mortar cavity due to leakage was included. Predicted mortar performance of several ideal and non-ideal explosives were in good agreement with experimental values. The effects of slow and incomplete reaction of non-ideal compositions have been demonstrated, and it has been shown that measurement of mortar throw angle alone is insufficient to determine the performance of a composition. The model has been used to elucidate the reaction rate behaviour of Ammonium Nitrate and Aluminium in commercial explosives.

## INTRODUCTION

The ballistic mortar has been used for over a hundred years by commercial explosives companies to measure the total available energy of their compositions, and to provide a practical ranking of explosive performance. Throughout its history, the mortar had provided a self-consistent ranking for nitroglycerine sensitised compositions, but with the advent of dry blasting agents, water gels, and more recently emulsion explosives it had been shown that mortar rankings were not maintained across different classes of explosives, nor always within one class itself[1]. Often novel explosives performed in a manner which belied their mortar ratings.

There is strong evidence that the physical form and chemical reactivity of ingredients can have important effects on the performance of commercial explosives[2]. It is possible that the variable mortar performance of such explosives could be caused by non-ideal behaviour, and that a model of the mortar which included chemical reaction rate, could be used to resolve such factors.

Previous analyses of the mortar have demonstrated the classical mechanics of the system[3] and the effect of charge geometry and initiator size[4]. In this work a classical mechanical analysis has been coupled to a phenomenological reaction rate model, allowing independent investigation of total available energy and chemical reactivity on the performance of the explosive.

## A REACTIVE MODEL FOR THE BALLISTIC MORTAR

The mortar can be considered as a rigid pendulum, consisting of a two piece bob supported by stiff metal plates from a knife edge (Figure 1). During the mortar test 0.01 kg of explosive, cartridged in tin foil, is placed in the free space in the bob. A small copper detonator is used to initiate the composition and the resulting explosion and expansion of detonation products accelerates the projectile and bob in opposing directions, eventually driving the projectile out of the bob. The bob continues to move ballistically until a maximum deflection angle is reached. The angle reflects the power of the explosive composition.

The behaviour of the explosive-mortar system was modelled in three phases: the initial reaction of the composition to form a hot high pressure gas within the free space; the expansion of the gas, performing work against the projectile and the bob; and the ballistic motion of the bob after the projectile had exited. Non-ideality was introduced by modifying the initial state of the gas and including energy release and gas generation or loss terms in the expansion phase.

## Initial Conditions

The initial conditions in the mortar cavity were obtained from the thermochemistry of the system and the elemental explosive composition. The Harries BLEND[5] equation of state was used to calculate the heat of reaction of the composition and the PVT state of the gas in the mortar cavity. BLEND can be written as

$$p = \frac{AE(1 + B\sigma_0)^3}{1 + 2B\sigma_0} \qquad (1.1)$$

where p is pressure, $\sigma_0$ the initial density of the explosive, B

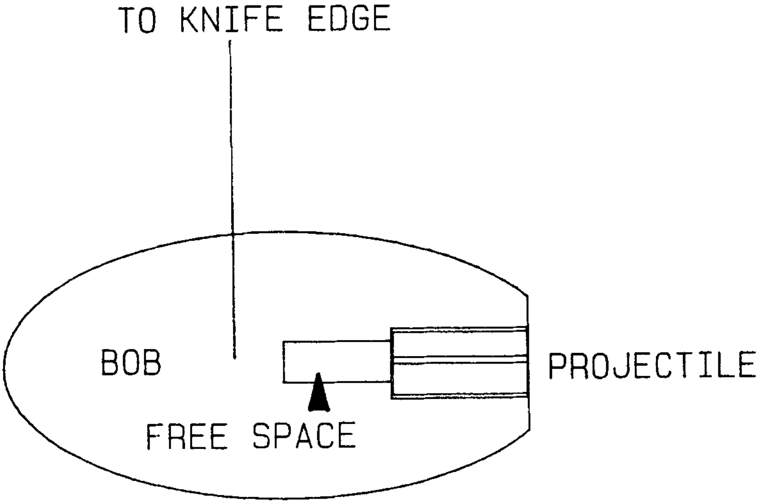

FIGURE 1
The Ballistic Mortar

the covolume of the detonation products, E the specific internal energy of the products, and A is defined by

$$A = \frac{C_v - C_p}{C_v} \qquad (1.2)$$

where $C_v$ and $C_p$ are the constant volume and constant pressure specific heats of the explosion products at s.t.p.

The post explosion state was calculated from equation 1.1 assuming an initial density that would be obtained if the explosive were uniformly distributed throughout the mortar free space, and assuming, in the case of ideal explosives, a chemical composition given by the test sample mixed with the PETN base charge of the initiator. In the case of non-ideal behaviour the specific energy and gas concentration were reduced from the ideal value by an amount consistent with incomplete chemical reaction of slowly burning ingredients.

Expansion Phase

From the BLEND post-explosion state, the gaseous products were expanded adiabatically performing work on the projectile and the bob. During the expansion process gas was allowed to escape from the system by leakage, at the local escape velocity, between the bob and projectile. Such energy and gas that was not released due to non-ideality in the explosion phase, was released during expansion in a fashion which represented the physical processes of particle ignition and erosive grain burning.

Treating the mortar as a classical rigid pendulum in which energy released by the expanding gas was partitioned between the bob and projectile conserving both momentum and energy, gave

$$I_pW_p = I_bW_b \tag{2.1}$$

$$I_pW_p^2 + I_bW_b^2 = E_w \tag{2.2}$$

where I denoted moment of inertia; W angular velocity about the point of suspension; subscripts p and b refer to projectile and bob respectively; and $E_w$ is the work performed by the expanding gas.

Taylor has shown that $I_p$ and $I_b$ can be derived from the structure of the mortar[6] such that

$$I_p = m_p r^2_{pc} \tag{2.3}$$

$$I_b = m_b S_b l_b \tag{2.4}$$

where m denoted mass; S the distance between centroid and knife edge; l the dimension of an equivalent simple pendulum; $r_{pc}$ the distance from the knife edge to projectile centre of mass; and subscripts are as above.

The release of energy by the gas during expansion, and hence the work done on the mortar assembly was given by

$$E_w = \int_{v_1}^{v_2} \frac{p_1 v_1^{\alpha}}{V^{\alpha}}\, dv \tag{2.5}$$

where p was pressure; v volume; α the adiabatic exponent of the gas; and subscripts 1 and 2 refer to the initial and final states of the gas.

The state of the gas during expansion was given by a perfect gas equation of state (the low pressure asymptote of BLEND).

$$pv = nRT \tag{2.6}$$

where n denotes moles of gas; and T temperature.

The model was developed by addition of time dependent terms to include chemical reaction rate effects, partial chemical reaction, and changes in the product gas concentration due to leakage and chemical reaction.

For any time dependent expansion, equations 2.1 to 2.6 and those decribing the rate of volume change with time, and the rate of gas and energy liberation by chemical reaction, and the rate of gas leakage must be satisfied:

$$\dot{v} = \pi r_p{}^2 \left(\frac{W_b}{S} + \frac{W_p}{r_{pc}}\right) \tag{3.1}$$

$$\dot{n} = 4\pi n_p r_r^2 \dot{r}_r - \frac{2\pi r_p c l_o n}{v} \tag{3.2}$$

$$\dot{q} = 4\pi q_r r_r^2 \dot{r}_r - \frac{2\pi r_p c l_o nq}{v} \tag{3.3}$$

$$\dot{r}_r = ap^b \delta(t_i) \tag{3.4}$$

$$l_o = \frac{2\sqrt{(\alpha pv)}}{\alpha - 1} \tag{3.5}$$

$$\dot{p} = \frac{n\dot{q}}{v} + \frac{\dot{n}q}{v} - \frac{\dot{v}p_1 v_1{}^{(\alpha+1)}}{v^{(\alpha+1)}} \tag{3.6}$$

where $r_p$ was projectile radius; $n_p$ the moles of gas generated or adsorbed per unit reactant; c the clearance between bob barrel and projectile; $l_o$ the local escape velocity; q the total heat in the gas; $q_r$ the energy released per unit reactant; $r_r$ the reactant particle radius; a,b coefficients of the grain burning kinetics;

and $\delta(t_i)$ is a unitary step function of the particle ignition time.

Equations 3.1 to 3.6 were integrated numerically to give the PVT state in the cavity, the projectile and bob velocities, and the state of chemical reaction during the expansion process.

The Ballistic Phase

At the instant the projectile left the bob, the gas ceased to perform work on the system and the bob energy could be calculated from either the bob or projectile velocities.

$$E_b = \tfrac{1}{2} m_b S_b l_b W_b{}^2 \qquad (4.1a)$$

$$E_p = \tfrac{1}{2} \frac{(m_p v_p r_{pc}{}^2)^2}{m_b S_b l_b} \qquad (4.1b)$$

The bob was allowed to continue to swing ballistically against gravitational force to reach a maximum angular displacement, at which point the kinetic energy was fully converted to potential energy. The maximum angle was therefore given by

$$\beta = \arccos\,(1 - E_b/m_b S_b g) \qquad (4.2)$$

where g is the gravitational constant.

The angle, β, reflected the total energy released and could be used to rank explosives absolutely, or if expressed in terms of a percentage, the performance relative to some standard, usually Blasting Gelignite (BG).

$$\%BG = 100\,\frac{1 - \cos\beta}{1 - \cos\beta_{BG}} \qquad (4.3)$$

## PERFORMANCE OF MODEL

Comparisons were carried out between the predicted and experimental values of maximum throw angle and %BG, as defined in equation 4.3, for a series of ideal intramolecular explosives and a series of intimately mixed intermolecular composition, the particle size of which made them virtually ideal.

In the experiments 10g of explosive was cartridged in tinfoil and initiated with a copper detonator containing 0.08 g PETN. Each composition was tested in triplicate and the results averaged to provide a figure of merit. The mortar cavity was mechanically scoured between shots to remove debris and deposits. Between each composition a number of shots of BG were fired to provide a constant reference state. The tests were modelled assuming all the explosive reacted in the initial explosion. No adjustable parameters were used, as the mortar physical dimensions were well known from other work[7].

Excellent agreement was obtained between the measured and calculated throw angles and %BG for all the compositions tested with the exception of TNT powder (Tables 1 and 2). The overestimation of the performance of TNT is thought to be associated with the formation of large quantities of solid products which cannot remain in thermal equilibrium with the gaseous products during expansion and therefore act as a sink for thermal energy.

## TABLE 1
## Comparison of Absolute Throw Angle

| Explosive | Model<br>deg | Experiment<br>deg |
|---|---|---|
| BLASTING GELATINE | 18 20' | 18 30' |
| EMULSION | 15 27' | 15 35' |
| SUPERFINE AN FUEL OIL | 16 35' | 16 43' |

## TABLE 2
## Comparison of Results in Terms of % Blasting Gelignite

| Explosive | Model<br>%BG | Experiment<br>%BG |
|---|---|---|
| PETN | 101.0 | 102.0 |
| TNT | 67.0 | 64.8 |
| PENTOLITE | 87.0 | 87.0 |
| MAN/AN WATERGEL | 65.0 | 64.0 |
| EMULSION | 69.0 | 69.0 |
| ALUMINIZED EMULSION | 79.0 | 79.0 |
| SALT DOPED EMULSION | 59.0 | 59.0 |
| p.g. ALUMINISED SLURRY | 79.0 | 79.0 |
| SUPERFINE AN/OIL | 80.0 | 79.0 |
| SUPERFINE AN/OIL 5% ALUMINIUM | 83.0 | 80.3 |
| SUPERFINE AN/OIL 10% ALUMINIUM | 89.4 | 90.2 |
| SUPERFINE AN/OIL 15% ALUMINIUM | 92.2 | 91.2 |
| SUPERFINE AN ALUMINIUM | 90.4 | 92.3 |
| SUPERFINE AN GILSONITE | 79.5 | 80.2 |

## EFFECTS OF REACTION RATE

The reaction rate function, equation 3.4, has been used to examine the effect of non-ideal explosive behaviour on mortar performance. A numerical experiment was performed where only 50% of a composition was allowed to react during the explosion phase, the remainder burning during the expansion phase. The explosive was assumed to be granular in nature, and two distinct classes of reaction behaviour were considered:

(i) that the ignition time was very short but the reaction rate slow;

(ii) that the ignition time was long but the reaction rate fast.

These cases covered the behaviour of the two most common ingredients in commercial explosives : inorganic oxidisers that react by grain erosion; and metallic fuels that react by ignition and subsequent erosion.

## Case 1: Incomplete reaction.

The first case modelled was that of instantaneous constant volume reaction after a prescribed ignition delay. The simplest case, that of infinite delay, resulted in the expected behaviour: that mortar performance depended linearly on the total extent of reaction of the test composition (Fig 2).

## Case 2 : Complete Reaction with Ignition Delay

The degree of reaction in the initial explosion was held constant at 0.5, and the ignition delay varied from zero, i.e. full reaction in the explosion, up to 5µs, which was after the projectile had exited the bob. The resultant pressure-time profiles in the mortar cavity showed the effect of the constant volume reaction on the system. (Figure 3) The work done by each of these expansions was different, and decreased with increasing ignition delay. This was reflected in the effect of ignition delay on the %BG (Figure 4).

It was clear from these calculations that %BG did not provide

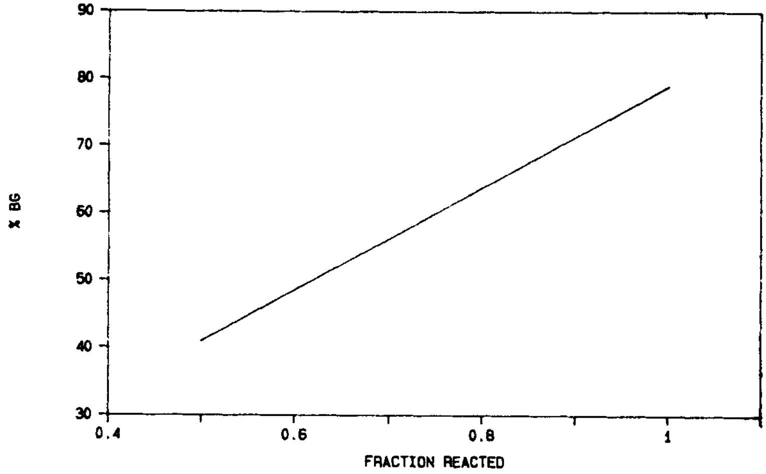

FIGURE 2
The Effect of Non-Reaction on Mortar Performance

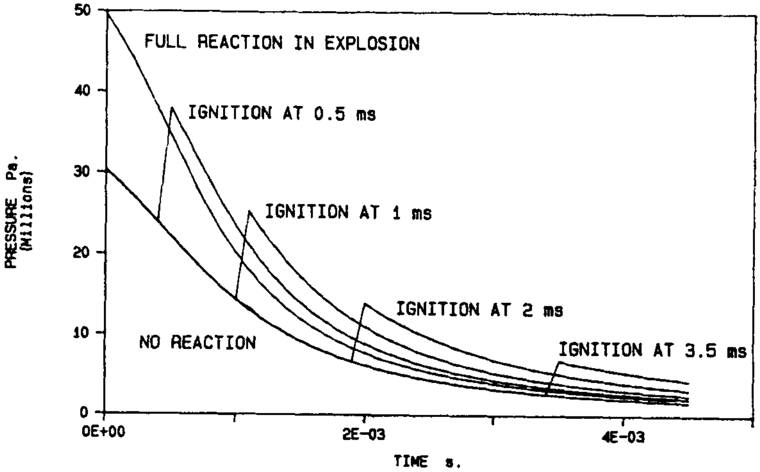

FIGURE 3
Ignition Delayed Reaction Pressure Profiles in Mortar Cavity

a unique method of defining explosive performance. A composition could attain the same rating either by incomplete reaction or by slow complete reaction. Explosives with identical %BG might therefore perform radically differently under field conditions where the timescale of the event differed significantly from that of the mortar.

## Case 3 : Complete Reaction with Finite Reaction Rate

The degree of reaction in the initial explosion was again held constant at 0.5 but the ignition delay was set to zero and the reaction rate constants varied to provide various grain burning profiles (Figure 5). The effect of such reaction on the pressure time profile in the mortar cavity was quite different from Case 2. (Figure 6). There was, however, still some effect on mortar performance (Figure 7).

The effect of grain burning on mortar performance was much less than the effect of ignition delay : the pressure dependency of the rate controlled the reaction, such that if it was to be completed before the projectile left the bob, approximately 80% of the reaction had to occur in the first millisecond of the expansion. Complete reaction in the mortar under grain burning kinetics should therefore be similar to a constant volume instantaneous reaction at 1µs. Both gave 73% BG performance. If the constraint of complete reaction was removed then the effects of partial reaction and late time energy release were compounded and a catastrophic fall in %BG resulted.

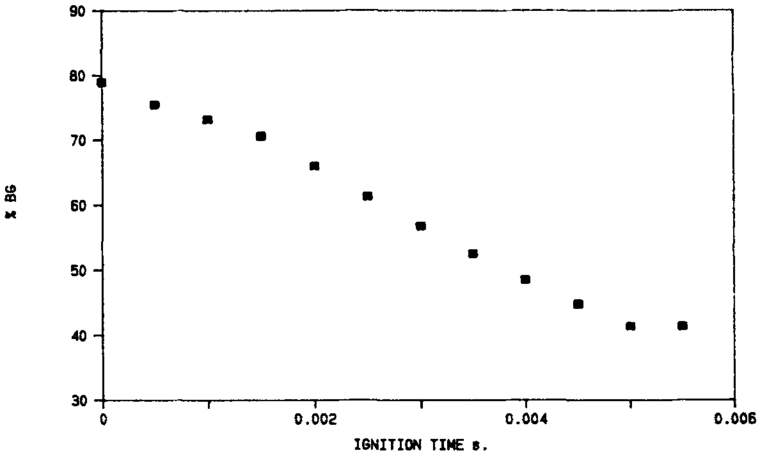

FIGURE 4
The Effect of Ignition Delayed Reaction on Mortar Performance

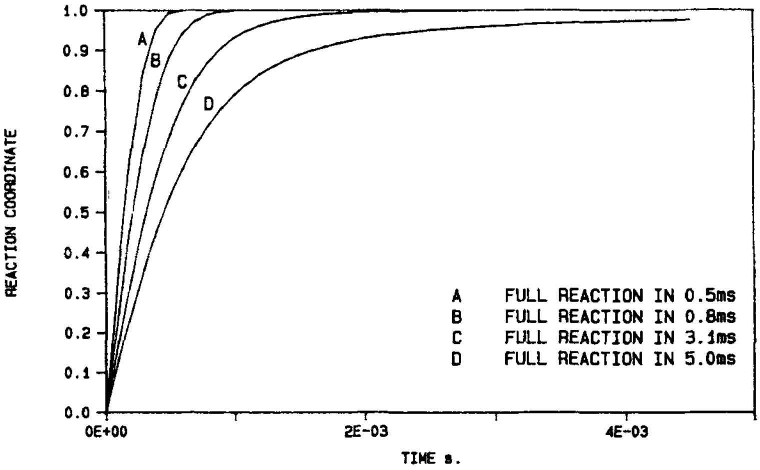

FIGURE 5
Grainburning Reaction Profiles in Mortar Cavity

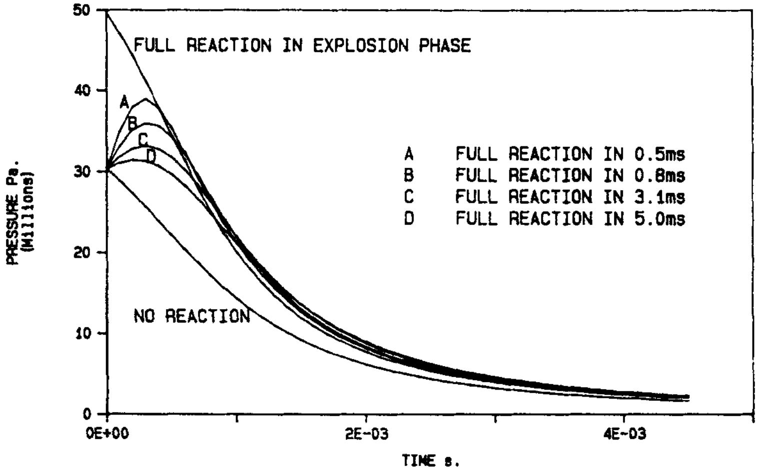

FIGURE 6
Grainburning Pressure Profiles in Mortar Cavity

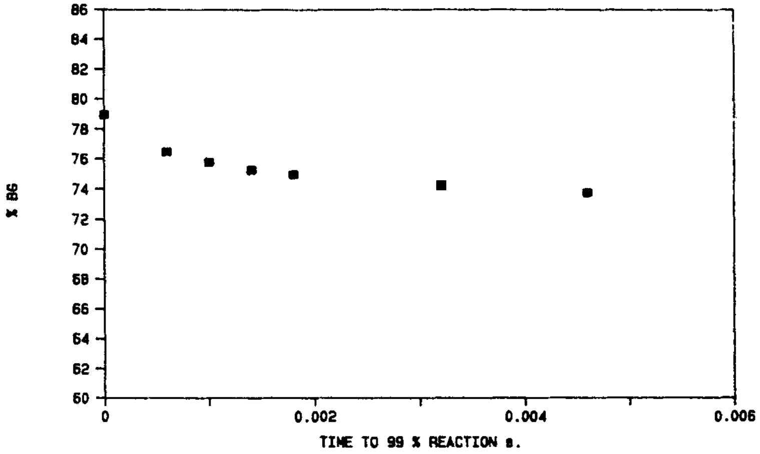

FIGURE 7
The Effect of Grainburning Reaction on Mortar Performance

## EXPERIMENTAL EVIDENCE OF NON-IDEAL BEHAVIOUR

Two common ingredients that are added as dopes to commercial explosives are atomised aluminium and crystalline ammonium nitrate (AN). These ingredients are regarded as energisers in that they are not required for the explosive to be detonable. In many cases non-ideal explosive behaviour may be attributed to the presence of these ingredients and by modification of their particle size, the degree of non-ideality can be altered[8].

Three explosives, ANFO, paint fine aluminium sensitised slurry, and emulsion were doped with variously sized aluminium and used to examine the effects of ignition delay on mortar performance. ANFO made from a variety of different AN prills was used to examine grain burning effects.

### Ignition Delay Effects

The theory of the ignition and burning of metal particles in hot oxidising atmospheres is well developed[9]. A two stage model is usually proposed consisting of an ignition event followed by relatively fast reaction[10]. In the case of aluminium the ignition event is rate controlling, and is associated with the need for thermal gradients in the particle to be shallow enough to allow exothermic oxidation on the surface of the particle to become self-accelerating. Macek has shown that for conductive heating, the ignition time of a particle is given by

$$t_i = \frac{\varepsilon d^2}{12\Phi}\left(c\ln\left(\frac{T - T_o}{T - T_i}\right) + \frac{H_1}{T - T_m}\right) \qquad (5.1)$$

where $\Phi$ is the metal density, d the particle diameter, c the metal heat capacity, $H_l$ the latent heat of fusion, $T_o$ the initial metal temperature, $T_m$ the metal melting point, T the gas temperature far from the particle, ε the gas thermal conductivity and $T_i$ is the ignition temperature given by

$$T_i = T_s - Kp_0^{.41} \qquad (5.2)$$

where $T_s$ is the melting point of the metal oxide, $p_0$ is the partial pressure of oxygen in the gas and K is a constant determined by experiment. Assuming that the aluminium does not react in the explosion phase of the mortar, an ignition time, which is a function of particle diameter, can be calculated for the initial cavity state achieved by each explosive (Figure 8).

Several general points emerged from this analysis: (i) that for any one particle diameter, ignitions in ANFO were faster than in slurry, than in emulsion; and (ii) that if the timescale of the mortar was of the order of 5 ms, as found both from theoretical and experimental analysis, aluminium should not react.

The ignition of metallic fuels is controlled by heat flow into the particle. Any increase in heat flow will reduce ignition times, allowing reaction in the mortar. Thermal transfer can be enhanced by local turbulence, and apparent increases of the order of 200 times, are not unreasonable. This would be sufficient to reduce ignition times to realistic values, for reaction in the mortar (Figure 8).

Based on the ignition delay effect calculated above, the behaviour of aluminised explosives in the mortar should have been

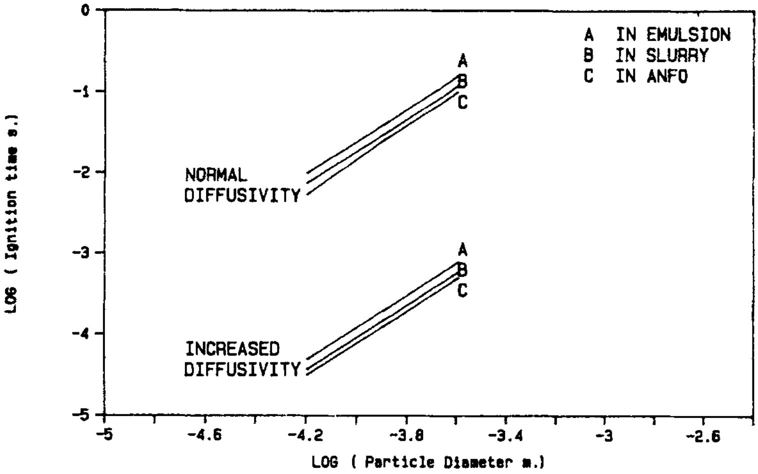

FIGURE 8
Ignition times for Aluminium in Various Atmospheres

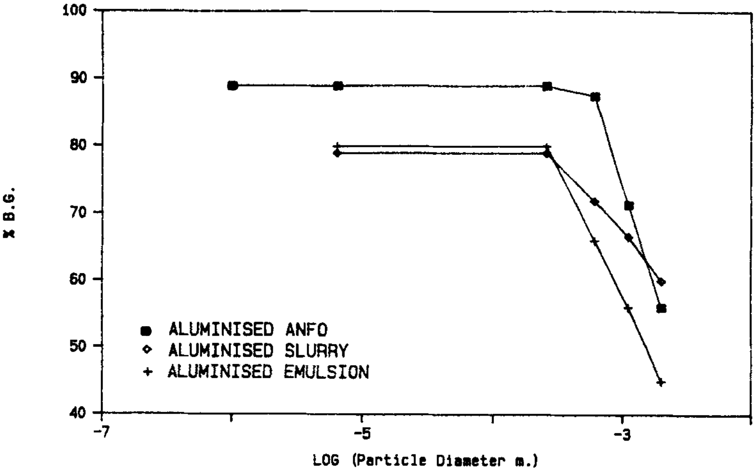

FIGURE 9
Experimental Data on the Effect of Aluminium Particle Size

independent of aluminium particle size till the aluminium failed to react in the explosion phase, thereafter as particle size, and therefore ignition time increased, the performance should have deteriorated. This hypothesis was supported by experimental evidence (Figure 9). The fall off in performance was also found to be explosive dependent, in agreement with the difference in ignition behaviour calculated from the theory of Macek: the fall off in performance of aluminised ANFO occurring between 256 and 600 μm,compared to between 150 and 256 μm in aluminised emulsion.

## Grainburning Effects

Crystalline ammonium nitrate is known to decompose exothermically to yield gaseous products. The rate at which the reaction proceeds through a crystal, known as the linear burning rate, is a function of the gas pressure above the crystal[11] The burning rate V can be represented by a standard propellant rate law:

$$V = ap^{b} \qquad (6.1)$$

Literature data has been used to provide a fit to this general relationship over five orders of magnitude in pressure, (Figure 10).

A series of ANFO explosives were manufactured from AN prills of greatly differing specific surface areas giving a range of equivalent spherical diameters (ESD) from 8μm to 59μm ( equivalent spherical diameter being defined as the diameter of spherical particles of equivalent specific surface area to the AN prills ).

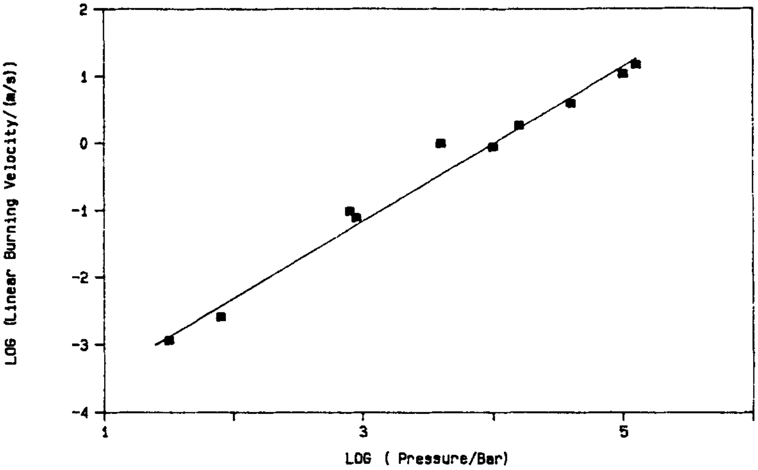

FIGURE 10
Effect of Pressure on the Linear Burning Rate of Ammonium Nitrate

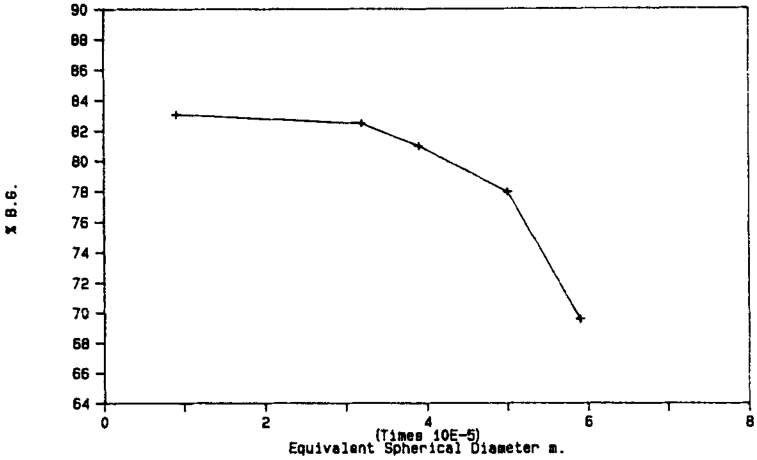

FIGURE 11
Experimental Data on the Effect of Ammonium Nitrate Particle Size

The mortar performance was found to vary slowly with ESD up to 30μm (Figure 11). From 30 to 50 μm ESD, the performance fell slowly, and beyond 50 μm the performance dropped markedly. The different regimes were interpreted as being complete reaction in the explosion phase up to 30 μm ESD, grain burning to full reaction in the expansion phase between 30μm and 50μm ESD, and grainburning to partial reaction above 50μm ESD.

The model was used to predict the mortar performance as a function of ESD. The initial cavity condition was calculated assuming only the initiator reacted, the ANFO being burned during the expansion phase. Qualitative agreement with experiment was obtained and the predicted grainburning profiles supported the interpretation of the experimental data (Figure 12).

## CONCLUSION

A model of the Ballistic Mortar test has been constructed which highlights the effect of chemical reaction rates in mortar performance. Good agreement between experiment and model results have been obtained for both non-ideal and ideal explosives. It has been demonstrated that the behaviour of aluminium and ammonium nitrate can be accounted for in detail by considering the reaction process. It has been demonstrated that the ignition behaviour of aluminium in explosives is formulation dependent, in the same way as in fuel-air and propellent flames.

The use of mortar throw angle as a measurement of performance has been shown to be non-specific. in that identical throw angles

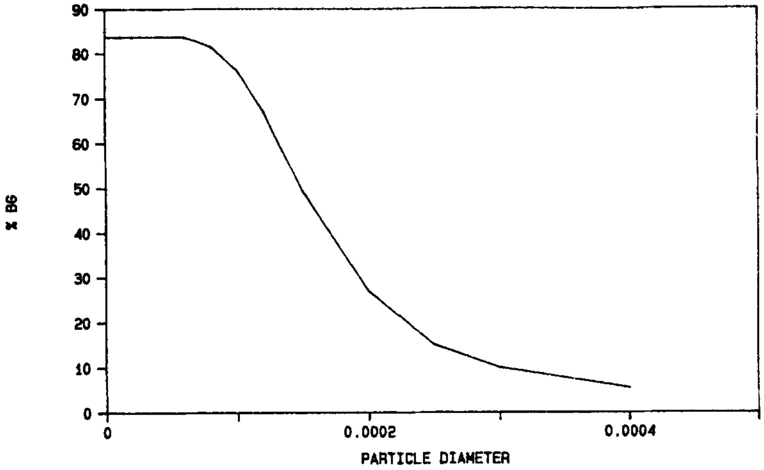

FIGURE 12
Model Prediction of the Ammonium Nitrate Size Effect

can be obtained for a number of reaction rate behaviours. The mortar has been shown to respond to changes in reaction rate behaviour at relatively early time in the expansion and hence provides a method of ranking explosive for use in blasting.

## ACKNOWLEDGEMENTS

The author wishes to thank Dr C.M. Lownds and Mr. G. Harries for helpful discussions during development of this model, and to thank Mr M. Harding for preparing the explosive samples. The permission of Nobels Explosives Company to publish this work is gratefully acknowledged.

## REFERENCES

1. C.M. Lownds, private communication
2. M.A. Cook, "The Science of High Explosives", Reingold, New York, 1958
3. W. Taylor and G Morris, Trans. Faraday Soc., 28, p545, 1932
4. G. Johanson and P.A. Persson, "Detonics of high Explosives", Academic Press, London, 1970
5. G. Harries, private communication
6. W. Taylor, I.C.I. Report R1.3249, 1931
7. W. Taylor, I.C.I. Report R1.3414, 1931
8. G.A. Leiper, to be published
9. R Friedman and A. Macek, in " Proceedings of the 9th Symposium (Intnl) on Combustion", The Combustion Institute, Pittsburgh, 1963
10. A. Macek, in " Proceedings of the 11th Symposium (Intnl) on

Combustion", The Combustion Institute, Pittsburgh, 1967

11. N.N. Bakhman and A.E. Belyaev, "Combustion of Heterogeneous Condensed Systems", Nakua, Moscow, 1967